

A Comparison of Methods for the Detection of Myocardial Ischemia During Noncardiac Surgery: Automated ST-Segment Analysis Systems, Electrocardiography, and Transesophageal Echocardiography

John E. Ellis, MD, Manish N. Shah, BA, Joan E. Briller, MD, Michael F. Roizen, MD, Solomon Aronson, MD, and Steven B. Feinstein, MD

Department of Anesthesia and Critical Care and Department of Internal Medicine, The University of Chicago, Chicago, Illinois

Clinicians often fail to detect intraoperative ischemic electrocardiographic (ECG) changes when viewing oscilloscopes. Automated ST-segment monitors promise to increase the detection of such ECG changes. We investigated the capacity of two commercially available ST-segment monitors to detect intraoperative myocardial ischemia in patients at high risk for developing intraoperative myocardial ischemia during vascular and other noncardiac procedures. The ST-segment monitors were compared with two reference monitors: (a) printed eight-lead ECGs, as interpreted by a cardiologist, and (b) the presence of segmental wall motion abnormalities and thickening abnormalities detected by transesophageal echocardiography (TEE). We also examined the capacity of the printed ECG to diagnose myocardial ischemia when compared with TEE. We studied 44 patients who underwent TEE, printed multilead ECG, oscilloscope monitoring of leads V₅ and II, and measurement of ST-segment deviation from the baseline using an automated Hewlett Packard ST-segment device. The sensitivities for the Hewlett Packard system were 40% for TEE-diagnosed myocardial ischemia and 75% for ECG-diagnosed ischemia.

Comparison of the printed ECG with TEE revealed that ST-segment changes in the printed ECG, as analyzed by a cardiologist, were 25% sensitive and 62% specific for the detection of TEE-diagnosed myocardial ischemia. When T-wave inversions were added to ST-segment depression as a criterion for the diagnosis of myocardial ischemia by the printed ECG, the sensitivity of ECG for the detection of intraoperative myocardial ischemia, as determined by TEE, was 40% and specificity was 58%. Twenty-three of the 44 patients were simultaneously monitored in leads I, II, and V₅ with an automated Marquette ST-segment monitor. In the 23 patients monitored with both Hewlett Packard and Marquette systems, the sensitivities (80% vs 100%, respectively) and specificities (67% vs 50%, respectively) were similar for ECG-diagnosed myocardial ischemia. Monitors of intraoperative myocardial ischemia often do not agree with each other; however, automated ST-segment monitors predict most ischemic changes seen on the printed ECG and can be used as an alarm to alert the clinician to examine the ECG.

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Recent work has documented the high incidence of perioperative ischemia in patients with peripheral vascular disease (1) and in those with known coronary artery disease (2). In patients undergoing coronary artery bypass grafting procedures, perioperative myocardial ischemia has been associated with an increased risk of perioperative myocar-

dial infarction (3). In patients undergoing noncardiac surgery, ST-segment depression detected by Holter monitoring after surgery predicts a ninefold increase in the risk of ischemic postoperative events (4). Because myocardial ischemia is often not detected by clinicians when viewing oscilloscopes (5), automated vigilance of the ST segments of the electrocardiogram (ECG) has been proposed as a method to alert clinicians to changes in the ECG (6,7).

Several instruments that continuously monitor deviation of the ST segment at a defined point in the cardiac cycle are now available. Although this technology has been used to define demographic predic-

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Address correspondence to Dr. Ellis, Department of Anesthesia and Critical Care, The University of Chicago, 5841 South Maryland Avenue, Box 428, Chicago, IL 60637.

tors of intraoperative myocardial ischemia (8), ST-segment monitors have not been compared directly with other established techniques for the detection of intraoperative myocardial ischemia.

The goal of this study was to assess this new ST-segment monitoring technology. Accordingly, we tested the hypothesis that ST-segment trend analysis could detect intraoperative ischemia as well as two commonly used techniques: (a) analysis of printed multilead ECG by a cardiologist, and (b) the detection of abnormalities in wall motion using two-dimensional transesophageal echocardiography (TEE). We compared two ST-segment trend monitors with ECG and TEE detection of intraoperative myocardial ischemia to determine sensitivity, specificity, positive predictive rate, and negative predictive rate for the two ST-segment trend monitors. In determining these rates, printed ECG and TEE were considered as standard reference monitors.

The need for determining these four rates when assessing new technology has been recently highlighted by Cooper et al. (9) who, in decrying the poor quality of early evaluations of magnetic resonance imaging, noted that "sound and scientifically rigorous evaluation of new technologies is necessary to insure quality of care and cost-effective use of resources." Rigorous technology assessment is crucial, for an unproved technology may not only prove costly, but may also delude the clinician into believing a sick patient normal or into initiating treatment when none is needed.

Methods

Patient Selection and Measurement Periods

After Institutional Review Board approval and patient consent, we studied 44 patients whose mean (\pm SD) age was 64 ± 12 yr. Of these 44, 35 underwent vascular reconstructive surgery (16 aortic, 12 carotid, and 7 femoral artery procedures). Nine other patients with significant risk factors for coronary artery disease undergoing other types of noncardiac surgery were also studied. Five were studied during laparotomy, and the remaining four underwent miscellaneous procedures. Those included in our study had at least two of the following risk factors: (a) age >70 yr, (b) history of hypertension, (c) history of peripheral vascular disease, (d) history of diabetes, (e) chronic renal failure, or (f) known coronary artery disease. The only exclusion criteria used were the presence of left bundle branch block pattern, a ventricular paced rhythm, or cardiac surgery. Left ventricular hypertrophy with "strain pattern" on ECG was not considered an exclusion. The ECGs were printed and ST-segment data recorded at 5 min

before and after induction of anesthesia and at 5 min after tracheal intubation. Complete measurements (ECG, ST segments, and TEE) were carried out for 15 s before and after incision and 5 min before and after vascular occlusion and reperfusion during major vascular surgery, whenever any of the monitors suggested myocardial ischemia or whenever major hemodynamic perturbations ($\geq 40\%$ change from baseline in heart rate or mean arterial blood pressure) occurred.

ST-Segment Trend Monitors

To each patient we applied the leads of one or both of two ST-segment monitors. The Hewlett Packard (HP) (Hewlett Packard, Waltham, Mass.) 78534C monitor was used in all 44 patients. This monitor measured the deviation of the ST segment at a point 120 ms after the R wave from a baseline defined at 80 ms before the R wave. Paced beats were discarded and the median value during a 15-s epoch displayed. These recordings were made in the diagnostic mode, within the frequency 0.05–100 Hz. The value of ST-segment deviation was measured in leads II and V_5 ; the absolute values of ST-segment variation in these two leads were summed and displayed by the monitor.

The ST-segment monitors display a total that represents the sum of the absolute values of ST-segment change in the monitored leads. Therefore, we prospectively defined myocardial ischemia as the increase of 1.0 mm in the sum of the absolute value of ST-segment score over the lowest absolute value (closest to no deviation) measured during the operative procedure. We assumed that most ischemic changes would be in one vascular bed and, therefore, in one lead at a time. The definition of myocardial ischemia as 1 mm or greater change in the summated leads is not standard. However, we chose this definition in an attempt to improve sensitivity and also because this summed presentation is the usual manner in which the monitor displays data to the clinician.

A second monitor, the Marquette (MQ) (Marquette, Milwaukee, Wis.) 7000 ST-segment trend monitor, was applied simultaneously to 23 of the patients in the HP group. This monitor became available after we began our studies with the HP system. The MQ monitor measured the ST segment at 80 ms after the J point in leads I, II, and V_5 , and summed the absolute values of ST-segment deviation from the baseline in the three leads. The monitor was used in a diagnostic mode, with a frequency response of 0.05–40 Hz. We prospectively defined myocardial ischemia as the increase of 1.0 mm over the lowest ST-segment sum during the case. When two ECG

monitors (HP and MQ) were applied, the electrodes were cut and attached so as to make them adjacent to each other for the same lead on different machines. We were aware that results obtained from the HP and MQ monitors might vary, because the HP monitor did not use a J-point reference. In addition, the MQ system used an additional lead (I). Neither of the ST-segment systems tested allowed adjustment of the point in the cardiac cycle at which the isoelectric baseline or the ST segment was measured.

Two-Dimensional Transesophageal Echocardiography

A TEE probe was placed in each of the 44 patients shortly after induction of anesthesia. Short-axis views at the midpapillary muscle level were recorded for 15 s simultaneously with ST-segment trend and ECG data, except for the period preceding tracheal intubation, when TEE was unavailable. The echocardiograms were read by a single cardiologist unaware of the clinical condition; wall motion in each of four quadrants was graded as 1 = normal, 2 = mild hypokinesis and thickening abnormality, 3 = moderate hypokinesis and thickening abnormality, 4 = akinesis and lack of thickening, 5 = dyskinesis. An increase in the wall motion score of 2 or greater was the definition of myocardial ischemia as detected by TEE. The baseline for each quadrant was considered to be the lowest score noted during TEE monitoring, not necessarily the initial TEE recorded after induction.

Electrocardiograms

The ECGs of all 44 patients were monitored with a five-cable system that allowed printing of the six limb leads (I, II, III, aVR, aVL, aVF), the V₅ lead, and the MCL₁ lead. These eight leads were printed at the same time that TEE images were recorded on videotape: (a) on arrival in the operating room, (b) before and after intubation (when TEE was unavailable), (c) before and after vessel occlusion and reperfusion (along with TEE), (d) whenever any of the modalities suggested myocardial ischemia (along with TEE), and (e) when there were hemodynamic perturbations as previously defined (along with TEE). These ECGs were reviewed by a second, independent cardiologist for the presence of myocardial ischemia; she was unaware of clinical conditions. Our prospective definition of myocardial ischemia on the printed ECG was 1.0 mm of downsloping ST-segment depression over the minimal value in any one lead or T-wave inversions occurring in more than one lead, or both. The ECG tracings for all 44 patients were available for analysis.

Table 1. Definitions of Rates Used in Technology Assessment

Technology in question (test)	Reference standard (disease)	
	+	-
+	A	B
-	C	D

Sensitivity = Positive test in disease = $A/(A+C)$.

Specificity = Negative test in health = $D/(B+D)$.

Positive predictive value = Disease with a positive test = $A/(A+B)$.

Negative predictive value = Healthy with a negative test = $D/(C+D)$.

Statistical Considerations

To determine the efficacy of the new technology, we compared it with accepted technologies and definitions of the disease state. To define sensitivity (how often the test is positive when the reference standard says the patient has the disease) and specificity (how often the test is negative when the reference standard says the patient does not have the disease), we first needed to define a reference standard. The TEE and eight-lead ECGs were used as two clinically available, separate arbitrary reference standards for the definition of intraoperative myocardial ischemia.

We pooled all periods of time for each patient so that any reading of myocardial ischemia detected during the patient's procedure resulted in that patient being considered to have had an ischemic event. Normal readings at all time periods were taken to indicate the absence of ischemia. Therefore, we determined how well the different ischemia-detection monitors predicted ischemia during an operation, not at each episode. Furthermore, we believe that pooling was necessary because of the different time frames after an ischemic episode in which each monitor is capable of revealing ischemia (10). However, we did note the incidence of ischemic ECG changes that occurred before placement of the TEE probe (i.e., during the stresses of induction, laryngoscopy, and tracheal intubation).

In addition, the positive predictive rate (the percentage of patients with an abnormal test who truly have the disease) and the negative predictive rate (the percentage of patients with a negative test who are truly healthy) were computed (Table 1).

Results

Hewlett Packard ST-Segment Monitors Versus Transesophageal Echocardiography as the Reference Standard

Forty-four patients had both HP ST-segment scores and TEE images available for comparison of the two

Table 2. Sensitivity and Specificity of Ischemia Detection Methods

Test	Arbitrary reference standard				
	TEE	HP	MQ	ECG	
				ST segment	ST segment + T-wave changes
TEE (n = 44)	×	Sens:47% Spec:56%	Sens:50% Spec:78%	Sens:62% Spec:58%	Sens:67% Spec:62%
HP (n = 44)	Sens:40% Spec:63%	×	Sens:43% Spec:75%	Sens:75% Spec:69%	Sens:50% Spec:68%
MQ (n = 23)	Sens:78% Spec:50%	Sens:80% Spec:54%	×	Sens:100% Spec:50%	Sens:83% Spec:47%
ECG (ST segment) (n = 44)	Sens:25% Spec:62%	Sens:35% Spec:93%	Sens:36% Spec:100%	×	Sens:67% Spec:100%
ECG (ST segment or T-wave changes, or both) (n = 44)	Sens:40% Spec:58%	Sens:35% Spec:78%	Sens:64% Spec:89%	Sens:100% Spec:89%	×

TEE, transesophageal echocardiography; HP, Hewlett Packard; MQ, Marquette; ECG, electrocardiogram; Sens, sensitivity; Spec, specificity.

modalities. When TEE was used as the reference standard of myocardial ischemia, the sensitivity of the HP system was found to be 40%. In the 20 patients with TEE ischemia, only 8 (40%) had an ST-segment score change of ≥ 1.0 mm. The specificity of the HP system was 63%; of 24 patients without a significant wall motion abnormality, 15 were without a 1.0-mm increase in their ST-segment score. The positive predictive rate was 47%; of 17 patients with a ≥ 1.0 -mm change in their ST-segment score, 8 had significant wall motion abnormalities by TEE. Finally, the negative predictive rate was 56%; of the 27 patients without ischemia by ST-segment analysis, 15 were without significant wall motion abnormality.

ST-Segment Monitors Versus Electrocardiography as the Reference Standard

In all 44 patients with ECG strips, the HP ST-segment device was compared with the reference standard of ST-segment changes on the printed ECG interpreted by a cardiologist. The sensitivity of the HP ST-segment monitor was 75% (6 of 8), the specificity 69% (25 of 36), the positive predictive rate 35%, and the negative predictive rate 93% compared with the printed ECG.

In the 23 patients in whom both the MQ and HP monitors were simultaneously applied, we also used the cardiologist's interpretation of the ST segments from the printed ECG as the reference standard for ischemia. Our results showed that the HP system was 80% (4 of 5) sensitive and 67% (12 of 18) specific, with a positive predictive rate of 40% (4 of 10) and a negative predictive rate of 92% (12 of 13). The MQ system demonstrated a sensitivity of 100% (5 of 5) and specificity of 50% (9 of 18), with a positive

predictive rate of 36% (5 of 14) and a negative predictive rate of 100% (9 of 9) (Table 2).

Printed Electrocardiography Versus Transesophageal Echocardiography as the Reference Standard

In the group of 44 patients, we determined the sensitivity of the printed ECG using TEE as our reference standard for ischemia detection. We examined ST-segment changes, both with and without T-wave inversions, in addition to the presence of isolated T-wave changes, to compute sensitivities and other indices of accuracy. When TEE was considered the comparison standard, sensitivity of ST-segment changes in the printed ECG was 25% (5 of 20), specificity 62% (15 of 24), positive predictive value 62% (5 of 8), and negative predictive rate 58% (21 of 36) (Table 2). When T-wave criteria were added to the definition of ischemia on the printed ECG, sensitivity increased to 40% (8 of 20), whereas specificity was 58% (14 of 24) (Table 2). For an isolated T-wave change, compared with TEE, the positive predictive value was 75% (i.e., three of four patients with isolated T-wave inversions had an ischemic TEE).

Timing of Ischemic Episodes

We also examined how often ECG changes occurred before insertion of the TEE probe. Three patients developed ischemia, as detected by ST-segment changes in the printed ECG before placement of the TEE probe; all three demonstrated subsequent evidence of ischemia as detected by TEE.

Myocardial ischemia occurred most commonly during defined periods of expected stress, such as intubation, incision, and vascular occlusion. Thirty-

Table 3. Comparison of the Incidence of Ischemic ST-Segment Changes in Patients With and Without Left Ventricular Hypertrophy on Preoperative Electrocardiogram

	Patients with LVH	Patients without LVH
Intraoperative ECG ischemia	1	7
No intraoperative ECG ischemia	8	28

LVH, left ventricular hypertrophy; ECG, electrocardiogram.
 $\chi^2 = 0.380$; 10% critical value = 2.706 (no significant difference).

two of the patients demonstrated myocardial ischemia by one or more of the modalities. Thirty of these 32 patients (94%) demonstrated ischemia during the defined sampling periods, whereas 15 of the 30 also had ischemia during additional time periods. Only two patients had ischemia only during the additional time periods in which measurements were made during abnormal hemodynamics, without manifesting ischemia during expected periods of stress. In these two patients, ischemia was detected by TEE and T-wave inversions in one and by ST-segment changes in the other.

Effects of Left Ventricular Hypertrophy on Incidence of Ischemia Diagnosed by Printed Electrocardiography

We did not exclude patients who had left ventricular hypertrophy (LVH) from this study, although the presence of LVH with repolarization changes ("strain") may make the diagnosis of myocardial ischemia by ECG difficult. The preoperative ECGs of all 44 patients were reviewed for the presence of LVH. Thirty-five patients did not have LVH, seven patients had LVH by voltage criteria without repolarization changes, and only two had LVH with repolarization changes. Neither of the patients with LVH with strain had intraoperative ST-segment changes of >1 mm. A comparison of the incidence of ischemic ST-segment changes in patients with and without LVH appears in Table 3; there was no significant difference.

Intraobserver Variability of Transesophageal Echocardiographic Readings

The videotaped echocardiographic recordings of 16 patients were analyzed 1 yr later by the same reviewer to establish intraobserver variability. In 10 of 16 (62%) patients reviewed, the observer agreed with his previous determination of the presence or absence of intraoperative myocardial ischemia. Five of the six patients who had discordant determinations had small disagreements: (a) a change from normal to

moderate hypokinesia read originally was later called a change to mild hypokinesia (four patients; all changed from a two-grade change to a one-grade change); and (b) a change from normal to moderate hypokinesia read originally was later called no change (one patient; a two-grade change). In one patient with baseline segmental wall motion abnormalities (SWMAs), the original reading detected no decrease in function, whereas repeat reading detected a change from moderate hypokinesia to dyskinesia (two-grade change). In 68 of the 88 (77%) episodes reviewed in these 16 patients, the observer agreed with the diagnosis of a normal or ischemic episode.

Discussion

Recent work has highlighted the common and deleterious, yet often unrecognized, nature of perioperative myocardial ischemia (4). Printed ECG and TEE may be used, but they are discontinuous and require physician attention. The use of automated ST-segment monitors has been reported to assist in the vigilance of anesthesiologists (5-7). Although such monitors have been used to document ischemia occurring during reported cases (5) and to define demographic risk factors for the development of intraoperative ischemia during cardiac surgery (7), ST-segment analysis has not been compared with other methods of detecting intraoperative myocardial ischemia.

Limitations of This Study

We used intermittent, brief recordings of TEE and printed ECG in this study. Therefore, it is possible that we missed other periods of ischemia. However, we studied patients during periods of operative stress, such as tracheal intubation and aortic occlusion, and during hemodynamic stress when we believed that ischemia would be the most likely to occur. When we sampled data at times other than the defined perioperative events (during hemodynamic abnormalities or suspected myocardial ischemia), it added little to the detection of ischemia: only two patients, for example, had ischemia detected during periods other than the defined perioperative events. The 18% incidence of myocardial ischemia (detected by ST-segment changes in intermittent printed ECG) in our patients is similar to that reported by other workers who have used continuous ECG monitoring during vascular surgery (11). We therefore believe that such an incidence of myocardial ischemia allows the comparison of the different detection modalities.

We decided to analyze our data by comparing the evidence of ischemia detected during an operation by

each monitoring modality rather than by comparing corresponding episodes. We pooled our data because of the temporal dissociation of ECG and TEE in detecting intraoperative myocardial ischemia. This temporal dissociation of ECG and TEE in detecting intraoperative myocardial ischemia has recently been demonstrated by London et al. (12). In that study, although 19 patients had ischemia detected by both modalities, simultaneous ischemia was detected in only 5 patients (12).

Limitations of Transesophageal Echocardiography in Detecting Myocardial Ischemia

A major limitation of TEE is its inability to monitor patients during one of the most stressful parts of surgery—tracheal intubation. Although TEE may be used in awake patients, insertion of the probe before induction of anesthesia might be uncomfortable and might produce additional stress in the patient; it would certainly complicate airway management. Transesophageal echocardiography was not available to us during induction of anesthesia and intubation of the trachea; however, all three of the patients who had ST-segment changes on ECG as evidence of ischemia during this period subsequently developed an ischemic TEE study during surgery.

Transesophageal echocardiography has at least three other limitations in its capacity to detect intraoperative myocardial ischemia. First, although the short-axis view at the midpapillary muscle level does demonstrate the mechanical function of regions subserved by all three major coronary arteries, this view will not detect apical abnormalities. Chung et al. (13) reported a patient who had an anteroapical myocardial infarction (documented by transthoracic echocardiography) after aortocoronary bypass, who demonstrated ST-segment elevation during surgery but whose TEE remained unchanged. As a corollary, it is also possible that if a patient has an apical scar, and the echocardiographer is not careful to maintain a short-axis view at exactly the same level, moving the view in and out of the area of scar may cause the false diagnosis of myocardial ischemia to be made. Second, it has been suggested that changes in afterload, rather than myocardial ischemia, can produce regional wall motion abnormalities. Kavanaugh et al. (14) found in a dog model that the area of wall motion abnormality produced by coronary artery occlusion indeed was greater than was the area of hypoperfusion; however, in that study, pharmacologically induced changes in afterload did not alter segmental wall motion. Third, the normal heart does not have homogeneous contractility; in canine experiments, the apex of the heart has been shown to have greater

systolic shortening than basal regions of the left ventricle (15). In those experiments, performed without coronary artery constriction, the differences in regional systolic shortening were statistically significant. However, it is not clear whether the regional heterogeneity was great enough that it would be confused with myocardial ischemia. For example, when dogs were anesthetized with 1% isoflurane, percent systolic shortening was 18% in the apex and 13% in the base; the addition of verapamil abolished the difference in percent systolic shortening, decreasing them to 10% and 9% respectively. It is unlikely that the change from 18% to 10% in the apex would be called hypokinetic relative to the change in the base (13% to 9%). Indeed, the apex is not routinely monitored with TEE. Lowenstein et al. (16), in a recent editorial, discussed animal work in which afterload was increased after a period of myocardial ischemia (17). They point out that although increased afterload does diminish systolic shortening in post-ischemic myocardium, the decrease does not appear to be of the magnitude that would be associated with a new SWMA. This lack of change would be even less likely to be considered a SWMA when thickening changes are also considered a criteria for SWMA diagnosis, as we believe necessary. Further work is clearly needed to define the sensitivity and specificity of TEE in detecting myocardial ischemia, particularly in the settings of "stunned" myocardium and varying afterload.

We found a disturbingly high intraobserver variability in the diagnosis of myocardial ischemia. In 16 patients in whom studies were reviewed twice, 1 yr apart, 5 patients had a change in diagnosis of intraoperative ischemia. Four of the five patients had a change from normal to moderate hypokinesis, later called a change to mild hypokinesis. We now believe that a change to moderate hypokinesis, which we prospectively defined as change that might represent myocardial ischemia, may not be so significant a change. Tischler et al. (18), using dipyridamole echocardiography to evaluate patients before vascular surgery, scored segments as normal, hypokinetic, akinetic, or dyskinetic; they required a change of one grade to diagnose ischemia. London et al. (12) scored segments as normal, mild hypokinesis, severe hypokinesis, akinesis, or dyskinesis; they required a change of two grades (i.e., from normal to severe hypokinesis) to define a SWMA as representative of myocardial ischemia. Even with these more stringent criteria, the detection of new severe hypokinesis did not appear to herald adverse outcome. The changes that we detected from normal to moderate hypokinesis may represent trivial episodes of myocardial ischemia, or not even myocardial ischemia at all.

ST-Segment Devices

When the HP ST-segment monitor results were compared with analysis of ST-segment changes in the printed ECG for each of the 44 patients, reasonable correlations were seen. The predictive negative rate was an impressive 93%; that is, when the ST-segment monitor never increased its score by ≥ 1.0 mm, only 7% of the patients developed intraoperative myocardial ischemia, as indicated by printed ECG ST-segment changes. In the smaller group of 23 patients monitored with both MQ and HP monitors, the additional use of lead I in the MQ system was associated with a somewhat greater sensitivity (100% vs 80%) and somewhat lower specificity (50% vs 67%). This finding is surprising, because the extra lead used by the MQ, lead I, is rarely associated with intraoperative ischemic changes, as has been demonstrated by London et al. (19). The lower positive predictive values of both devices suggest that they detect ST-segment change more often than does a cardiologist's interpretation, for potential reasons that are discussed later. Although it would be possible to compare the individual leads used to calculate the ST-segment sum with other standards for diagnosing ischemia, such would not be an appropriate technology assessment, because it is the sum of changes that the clinician is presented with to make decisions. Thus, we believed that the appropriate technology assessment utilized sums for comparisons.

Limitations of ST-Segment Devices

The automated ST-segment monitors have various technical limitations that may produce erroneous results. They do not adjust the isoelectric point or the point in the ST segment at which ischemic changes are measured during tachycardia, nor do they distinguish upsloping or downsloping ST segments. Although the isoelectric baseline of the HP device was always chosen at 80 ms before the R wave, the MQ algorithm was not available to us. The difference between the detection algorithms of HP and MQ might be highlighted by tachycardia, which may produce erroneous determinations of ST-segment changes. Tachycardia is associated with a shortened PR interval, a taller P wave, and deflection of the PQ segment below the isoelectric line (20). Using fixed (relative to the QRS complex) points for the isoelectric point may either cause the isoelectric point to be measured in the P wave, causing a normal ST segment to appear falsely depressed in comparison, or to be measured during a PR segment that is deflected below the isoelectric line.

False-positive determinations of myocardial isch-

emia by automated ST-segment devices may also be due to inaccurate measurement of the ST segment. It is not clear how the HP system's lack of a J-point reference affects results. For both systems, however, tachycardia may shorten the ST segment (21); measuring the ST segment at a fixed time of 120 ms after the height of the R wave (as is done by the HP system) may result in the "ST segment" actually being measured during the T wave. The resultant inaccuracy will depend on the polarity of that T wave. Newer improvements (which were not available to us at the time of study) in both devices allow the clinician to view with a cursor at what point in the ECG the baseline and ST-segment measurements are being made and to alter the position of that cursor. This additional capacity may lessen artifacts due to tachycardia and abnormal isoelectric baselines; however, our study did not address this hypothesis.

A comparison of the patients who were monitored with the HP and MQ monitors revealed that 8 of 23 patients had discordant results. We do not have printouts from the MQ monitor to verify its algorithm, because we recorded the values displayed on the oscilloscope. In the eight patients with discordant results, we noted that MQ was positive in six patients and HP was positive in two. This is not surprising, given the higher sensitivity of the MQ system in detecting ECG ischemia. Even in these discordant cases, the differences between the maximal intraoperative change in absolute sums in the two systems were small. The differences ranged from 0.3 to 1.6 mm. Of note, three of these discordant results (MQ positive, HP negative) occurred because the change in the MQ was exactly 1.0 mm.

Others have shown that different operating room ECG systems may vary in their capacity to detect myocardial ischemia. Slogoff et al. (22) have recently demonstrated that ECG systems may vary in the amount of ST-segment change detected in patients undergoing coronary artery bypass graft surgery. Some of these differences appear to be due to the use of 0.5 Hz as the lower end of the frequency response range for many operating room monitors. In such cases, the use of the monitoring mode increases the incidence of myocardial ischemia (ST-segment changes of >1.0 mm) seen in coronary artery bypass graft surgery patients before cardiopulmonary bypass. Although 8.3% of patients demonstrated ischemia by these criteria in lead V₅ on a Holter monitor, and 12.8% of patients demonstrated ischemia by these criteria on a standard 12-lead ECG, the incidence of ischemia detected by an operating room monitor in that study was 27.5% (22). This high figure is probably due to artifactual ST-segment depression caused by the 0.5-Hz filter. In our study, the printed ECGs were all done using a frequency range of

0.05–100 Hz, using the diagnostic mode. Hence, we believe that it is valid to compare the values of ST-segment change in the patients in our study with the other ischemia detection devices.

Transesophageal Echocardiography Versus Printed Electrocardiography (Ischemia Defined by ST Segments or T Waves, or Both)

When data were examined for all periods during the operative procedures, we found that TEE and analysis of the ST segments of printed ECGs had the capacity to detect myocardial ischemia similar to previous series of high-risk patients undergoing non-cardiac surgery. When TEE was taken as the reference standard, the sensitivity of the printed ECG was only 25% for ST-segment changes and 40% for ST-segment changes or T-wave inversions, or both. Smith et al. (23) reported that during aortic and coronary bypass surgery, TEE detected intraoperative myocardial ischemia in four times as many patients as did printed ECG, with ST-segment depression used as a criteria. We found that the addition of T-wave criteria for the detection of myocardial ischemia using the printed ECG increases the sensitivity of the printed ECG from 25% to 40% compared with the reference TEE. We had decided prospectively to examine the usefulness of adding T-wave inversions in the definition of myocardial ischemia. We did this because previous studies had shown a low sensitivity for ischemia detection by ST-segment change compared with TEE. We hypothesized that the addition of the T-wave criteria might enhance capacity to detect myocardial ischemia. Supporting this hypothesis is a study of patients with resting T-wave inversions who underwent exercise radionuclide angiography stress testing (24). A significantly higher incidence (62% vs 28%) of new wall motion abnormalities was noted in patients in whom new T-wave inversions occurred compared with those without new T-wave inversion (24). T-wave changes were more sensitive, although less specific, than were ST-segment changes seen with stress ECG.

In reviewing data comparing mechanical, electrocardiographic, metabolic, and hemodynamic indicators of myocardial ischemia in patients with coronary artery disease undergoing vascular surgery, Haggmark et al. (1) suggested the possibility that "accepted criteria (ST segment changes only) for interpreting the ECG to indicate myocardial ischemia during anesthesia are too stringent." Our data concerning the association of T-wave changes with TEE ischemia might seem to confirm this, because three of four patients with isolated T-wave changes also developed new SWMA; however, the number of such patients

was very small. Other workers have suggested that T-wave changes are benign. Breslow et al. (25) concluded that T-wave inversions in the recovery room did not predict perioperative morbidity and mortality. However, the patient population in that study had a low "pretest probability" of having coronary artery disease. Our data, which show that three of the four patients with T-wave inversions in the absence of ST-segment changes had wall motion abnormalities, lead us to conclude that T-wave changes in a high-risk population may be associated with an ischemic TEE examination. However, we do not know whether either T-wave inversions or SWMAs were associated with adverse outcome in this study. The T-wave changes or SWMAs, or both, may be such sensitive indicators of myocardial ischemia that they may have a low predictive value for cardiac complications. Indeed, London et al. (12) showed that SWMAs were only associated with a 6% incidence of cardiac complications.

Automated ST-segment analysis devices are probably better than the "naked eye" in detecting ischemia, but they may be misleading. Because its positive predictive value is only 36% for the MQ system and 35% for the HP system as detected by our reference standard of TEE, each episode of ST-segment sum change of 1 mm or greater represents only approximately a one-third chance that the patients will be found to have myocardial ischemia by TEE. Our view, however, is that an ST-segment trend monitor should be considered an alarm that causes the clinician to increase vigilance. Thus, although our data do not prove our hypothesis that ST-segment trend analysis detects the same incidence of intraoperative myocardial ischemia as does printed multilead ECG or TEE, the two ST-segment trend monitors evaluated may prove useful to indicate the need for the anesthesiologist to examine the patients' ECG carefully. The indicators are useful because intraoperative ischemic episodes tend to be brief and therefore unrecognized by clinicians (12). Brief intraoperative ischemic episodes may herald longer postoperative episodes. If this were true, recognition of intraoperative ischemia may identify patients who might benefit from aggressive postoperative antianginal therapy; however, this is a hypothesis that remains unproved.

Further studies are needed to provide the clinician with reliable, inexpensive, and simple monitors for detecting intraoperative myocardial ischemia. In high-risk patients, ST-segment trend monitors may be used as an alarm, in conjunction with the review of printed ECG strips during surgery, potentially improving the detection of myocardial ischemia. However, these ECG modalities may not predict the presence of wall motion and thickening changes as

seen in TEE. Further study is necessary to determine which intraoperative monitoring devices are best for predicting patient outcome.

The lack of concordance of monitors of intraoperative myocardial ischemia leaves us unable to define a reference standard for its detection. The myocardial ischemia detected in this study was often not severe, which may explain the discordance of the different modalities and the relatively low intraobserver variability of TEE readings. The use of more stringent criteria may be needed to predict adverse patient outcome. However, because our study did not follow patients to determine the incidence of postoperative cardiac complications, we cannot compare the capacity of the different intraoperative monitors to predict adverse events. Both TEE and printed ECG appear from other studies to have low positive predictive values for postoperative complications. Changes in either monitor probably need to be severe and long-lasting to predict adverse outcome. The recent demonstration that postoperative myocardial ischemia occurs more frequently than intraoperative or preoperative ischemia (4) suggests that the capacity to diagnose intraoperative myocardial ischemia may be of limited value in predicting patient outcome.

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